Convective Planetary Boundary Layer Interactions with the Land Surface at Diurnal Time Scales: Diagnostics and Feedbacks

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ABSTRACT

The convective planetary boundary layer (PBL) integrates surface fluxes and conditions over regional and diurnal scales. As a result, the structure and evolution of the PBL contains information directly related to land surface states. To examine the nature and magnitude of land–atmosphere coupling and the interactions and feedbacks controlling PBL development, the authors used a large sample of radiosonde observations collected at the southern Atmospheric Research Measurement Program–Great Plains Cloud and Radiation Testbed (ARM-CART) site in association with simulations of mixed-layer growth from a single-column PBL/land surface model. The model accurately predicts PBL evolution and realistically simulates thermodynamics associated with two key controls on PBL growth: atmospheric stability and soil moisture. The information content of these variables and their influence on PBL height and screen-level temperature can be characterized using statistical methods to describe PBL–land surface coupling over a wide range of conditions. Results also show that the first-order effects of land–atmosphere coupling are manifested in the control of soil moisture and stability on atmospheric demand for evapotranspiration and on the surface energy balance. Two principal land–atmosphere feedback regimes observed during soil moisture drydown periods are identified that complicate direct relationships between PBL and land surface properties, and, as a result, limit the accuracy of uncoupled land surface and traditional PBL growth models. In particular, treatments for entrainment and the role of the residual mixed layer are critical to quantifying diurnal land–atmosphere interactions.

1. Introduction

Over the last two decades, a large number of studies have focused on methods to estimate regional land surface energy balance (Humes et al. 1994; Gillies et al. 1997; Norman et al. 2003). Conventionally, such studies use offline models of land surface processes, which require a great deal of observation and parameterization, and are limited by errors in their representation and model physics. Recently, the validity of land surface models that do not include the processes and feedbacks caused by land–atmosphere interactions has been under scrutiny. For example, results from the Project for Intercomparison of Land-surface Parameterization Schemes (PILPS; Henderson-Sellers et al. 1996) experiments have shown that simulated fluxes can be quite sensitive to atmospheric feedbacks (Liu et al. 2003, 2004, 2005). As a result, it is clear that the land surface and planetary boundary layer cannot be realistically simulated independently of one another, and that land surface models must, to some degree, be coupled to the atmosphere (Margulis and Entekhabi 2001). At the same time, fully coupled single-column, regional, and climate models are sub-

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stantially more complex, and therefore require significantly more assumptions, data inputs, and parameterizations for key processes relative to offline land surface models.

In this paper, we consider an approach to estimating land surface fluxes and states based on observations that enables one to identify the critical pathways and effects of land–atmosphere interactions. Specifically, the diurnal evolution of the convective planetary boundary layer (PBL) has been relatively unexplored as a means to infer land surface energy fluxes and moisture states. A variety of studies have shown that the structure of the PBL is influenced by the land surface in ways that can be identified and linked to surface conditions without the need for in situ measurements of such variables (Pan and Mahrt 1987; Oke 1987; Stull 1988; Diak 1990; Dolman et al. 1997; Peters-Lidard and Davis 2000; Cleugh et al. 2003; Ek and Holtslag 2004; Santanello et al. 2005). Further, the PBL integrates land surface processes at scales on the order of 10–100 km, thereby eliminating the need for upscaling of point models and measurements.

The most accurate in situ measurements of vertical gradients of temperature and moisture (and therefore PBL structure) in the lower troposphere come from radiosondes, and numerous attempts have been made to link these observations to land surface processes during short-term field experiments (Betts and Ball 1994; Peters-Lidard and Davis 2000; Yi et al. 2001). Recently, Santanello et al. (2005) evaluated a large sample of PBL and land surface data from the Atmospheric Radiation and Measurement Program (ARM) test bed in the southern Great Plains (SGP) and used these data to derive empirical relationships between PBL evolution and soil moisture on daily and regional scales. Their results suggest that there is significant potential for using observations of bulk PBL properties to gain information on the land surface states and processes.

Here we extend the work of Santanello et al. (2005) and examine the interactions that determine PBL evolution and land surface energy balance from an empirical and modeling perspective. In particular, the relationships among land surface properties and fluxes, PBL structure, atmospheric stability, and soil moisture are addressed. The specific goals of this research are to examine and clarify relationships among PBL and land surface variables across a broad range of conditions, and to identify feedbacks that impact and confound interpretation and prediction of the coupled system. To do this, we employ a single-column PBL model in combination with data from the ARM-SGP site. The strength and robustness of the relationships and coupling between PBL properties and surface conditions for a range of locations and land cover characteristics are explored using the model. Factors that complicate the relationships between PBL evolution, soil moisture, and surface fluxes are then addressed by considering the role of feedbacks between the PBL and land surface, which are then described and quantified using modeled and empirical data. Finally a two-step process to estimate regional surface fluxes is presented based on model results for a wide range of conditions.

6. Conclusions

In this paper, interactions between PBL height, initial stability, and soil moisture were examined using observed data and simulations from the OSU 1D PBL model. This model was able to reproduce surface and PBL conditions accurately at the ARM-SGP site, and statistical methods that relate PBL height to soil moisture were applied to a variety of surface and atmospheric conditions. Two feedbacks were identified that help to explain the manner in which interactions between the land surface and the atmosphere influence surface energy balance: 1) The negative feedback of PBL growth on soil drying and surface heating for intermediate soil moisture and 2) the positive feedback of entrainment on soil drying, surface heating, and residual layer growth for dry soils. These results were used to develop a framework for estimating surface moisture and sensible heat flux from observations of PBL properties. These techniques offer a strategy to obtain land surface information on daily and regional scales that does not require in situ observations, and also would provide results that satisfy the current needs of the meteorological and hydrological modeling communities.

Identification of the residual layer offers the opportunity to identify dry surfaces, predict future PBL growth, and assess the likelihood for drought. In the absence of significant changes in atmospheric forcing (frontal passage, rainfall, etc.), a strong and persistent residual layer can help to support drought conditions during soil moisture drydowns. The relationships and feedbacks examined here also highlight the fact that the PBL serves as a memory for surface conditions on diurnal scales (through h), and on longer time scales (through the interaction and feedback between the land surface and PBL). As a result, diurnal conditions such as atmospheric stability, and longer-time-scale processes such as soil moisture, are reflected in the evolution of PBL. Thus, the understanding and techniques developed here may also lead to a methodology to diagnose diurnal to seasonal changes in atmospheric and surface moisture conditions.